Multifragment Events From Heavy-Ion Collisions: Sources and Excitation Functions

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Multifragment events from 35, 40, 45, and 55 MeV/nucleon $^{139}La+^{12}C$, ^{27}Al, ^{40}Ca, ^{51}V, ^{nat}Cu, and ^{139}La reactions can be assigned to sources characterized by their velocity. At each bombarding energy, the probabilities of threefold, fourfold, and fivefold events increase substantially with decreasing source velocity, but are independent of the target mass. To remove the bombarding-energy dependence, a simple transformation has been applied which gives the excitation energy of the fused system in the simple incomplete-fusion picture. These "excitation functions" appear to be independent of both the system and bombarding energy.

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Intermediate-energy (20–60 MeV/nucleon) heavy-ion reactions have focused experimental[1,2] and theoretical[3,4] attention on multifragmentation and its possible association with the formation and decay of very hot nuclei.[5] At this energy the onset of multifragment events is expected. At higher incident energies ($E/A \sim 200$ MeV), average complex fragment multiplicities of up to ten have been observed in central collisions.[6] However, these fragments were not associated with well-defined sources.

A proper description of multifragment decay of hot nuclear systems requires the characterization of the source in terms of its size (mass/charge) and excitation energy, as well as of its branching ratios for the binary, ternary, etc., decay channels. Excitation functions for the various channels may provide the interpretative key to understanding whether the underlying decay mechanism is statistical or otherwise. Such excitation functions have been predicted by several theoretical models, such as sequential compound-nucleus decay[7] and simultaneous statistical multifragment decay of very excited nuclei.[3,4]

In the incomplete-fusion regime, heavy-ion beams produce nuclei with a range of masses, velocities, and excitation energies. Within the incomplete-fusion picture, for heavy projectiles on a light target, large impact parameters result in nuclei slightly heavier than the projectile moving at slightly less than the beam velocity and with small excitation energies. For smaller impact parameters, more mass is picked up from the target, resulting in slower, hotter, and heavier nuclei. For the 18-MeV/nucleon $^{139}La+^{64}Ni$ reaction, such a correlation was established between the degree of fusion (source velocity) and the mass and excitation energy of the product nucleus.[8] By relating the center-of-mass velocity of the binary events to the mass and excitation energy of the product nucleus, it was possible to study at one bombarding energy the decay properties of hot nuclei over an excitation-energy range extending up to 4 MeV/nucleon.

In this paper source velocity distributions have been obtained for twofold, threefold, fourfold, and fivefold events and we show that the n-fold events can be associated with characterizable sources. In our nomenclature an n-fold event consists of n coincident fragments ($Z \geq 4$) irrespective of their speculated origin, fission, or otherwise. The proportions of binary, ternary, quaternary, and quinary decay were determined for different bins of the source velocity. In this way, extended "excitation functions" were obtained for each reaction and bombarding energy. The remarkable result is that, except for the lightest target, ^{12}C, these excitation functions are very similar for all of the target-projectile combinations at four different bombarding energies. This result suggests a competition between the various multifragment decay channels independent of the entrance channel.

Beams of ^{139}La ions from the Lawrence Berkeley Laboratory Bevalac were used to study reactions on ^{12}C, ^{27}Al, ^{40}Ca, and ^{51}V targets at an incident energy of 35 MeV/nucleon, on ^{12}C, ^{27}Al, ^{40}Ca, ^{51}V, and ^{nat}Cu targets at 40 MeV/nucleon and on ^{27}Al, ^{51}V, ^{nat}Cu, and ^{139}La targets at 45 and 55 MeV/nucleon. In reverse kinematics reactions, the fragments have high kinetic energies and are emitted within a narrow cone around the beam direction. Thus, a satisfactory detection efficiency (∼40% for one fragment) was obtained by using two close-packed square arrays of nine Si(0.3 mm)-Si(5 mm)-plastic telescopes placed on either side of the beam. The angular coverage was 2°-26° in the horizontal and ±12° in the vertical plane. The 25-cm^2 position-sensitive Si devices yielded an angular resolution of 0.4°. At bombarding energies ≤ 45 MeV/nucleon, all fragments except the lightest ($Z \leq 3$), which will not be considered in the present analysis, were stopped in the 5-mm detectors. The ΔE-E measurements yielded unit charge identification up to $Z=57$ for most telescopes. The energy calibrations were performed by running several low-intensity beams with different atomic numbers directly onto all of the detectors,[9] and the error on these calibrations is less than 1.5%. The pulse-height defect in the Si detectors was significant for $Z \geq 25$ and a correction was applied.[10] The velocities of the fragments were inferred from their kinetic energy and charge, using the mass parametrization of Ref. 11.

Figures 1(a)-1(d) present the distributions of the sum of the measured charges for twofold events at $E_{lab}=35$ MeV/nucleon. (An n-fold event is defined as an event where n fragments of charge $Z \geq 4$ were detected.) For the ^{12}C target a narrow peak is observed. This peak broadens for heavier targets, reflecting the wider range of excitation energies resulting from the larger range of mass transfers, which gives rise to increasing amounts of light-particle evaporation. With increasing target mass, the tailing to low-Z values increases, and accounts for about 25% of the events in the case of the ^{51}V target. This tail is due to three- or four-body events where only two bodies were detected, and shows the increasing importance of multibody reactions for the heavier targets. The same distributions for threefold and fourfold events [Figs. 2(b) and 2(c) for ^{139}La+^{40}Ca] exhibit a peak at approximately the same total charge as the twofold events, but with a reduced low-Z continuum. In order to evaluate more precisely the effects of the detection acceptance, Monte Carlo calculations were performed in which the measured charge, energy, and angular distributions of the fragments were reproduced as faithfully as possible. In the case of the ^{40}Ca target at $E_{lab}=35$ MeV/nucleon, the contamination of the twofold and threefold events with incompletely detected higher multiplicity events was determined to be approximately 20%, when a gate was set on a total detected charge greater than 30. This contamination is smaller for lighter targets and larger for heavier targets and higher beam energies.

The following analysis is restricted to events where the total measured charge is at least 30, in order to insure a reasonable representation of the kinematical skeleton of the reaction and to keep the contamination arising from incompletely detected events to an acceptable level.

If the fragments originate from the decay of a single source, then its velocity is determined by $\mathbf{V}_s=\sum_i m_i \mathbf{V}_i/$

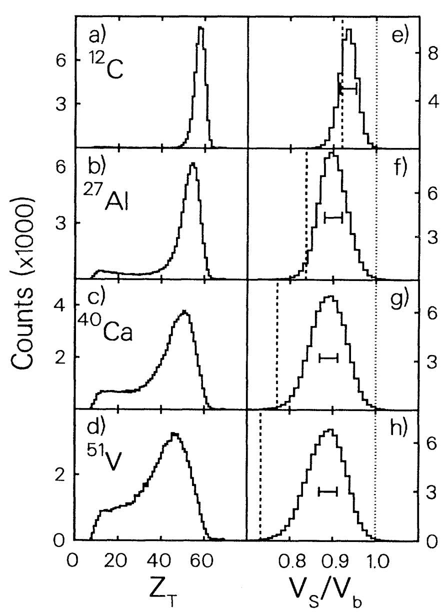

FIG. 1. (a)-(d) Distributions of the sum of the measured charges for twofold events for the 35-MeV/nucleon ^{139}La + ^{12}C, ^{27}Al, ^{40}Ca, and ^{51}V reactions. (e)-(h) Distributions of source velocities expressed as the ratio of the source (V_s) to beam velocity (V_b) for the same reactions. The dotted line indicates the beam velocity, and the dashed lines the source velocities expected for complete fusion. The horizontal bars indicate the expected broadening of the source velocity distribution due to light-particle evaporation for the mean excitation energy.

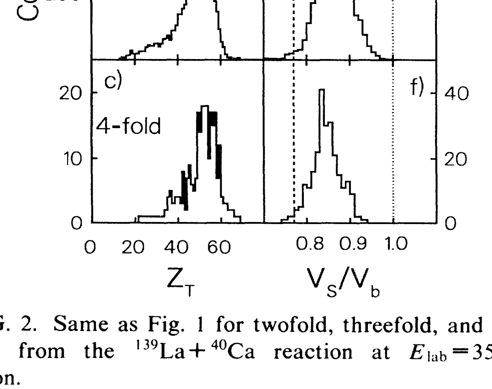

FIG. 2. Same as Fig. 1 for twofold, threefold, and fourfold events from the ^{139}La+^{40}Ca reaction at $E_{lab}=35$ MeV/nucleon.

$\sum_i m_i$. In the incomplete-fusion picture,[5] the excitation energy E^* is approximately related to the parallel source velocity V_s by $E^* = E_b(1 - V_s/V_b)$, where E_b is the bombarding energy and V_b the beam velocity. This formula does not take into account preequilibrium emission. Also, the recoil of the targetlike remnant due to the shearing off of the fusing part is neglected, but calculations[12] show that the excitation energies change by less than 20 MeV, which is much less than the experimental uncertainty.

Source velocity distributions for the ^{12}C, ^{27}Al, ^{40}Ca, and ^{51}V targets are presented in Figs. 1(e)-1(h) for the 35-MeV/nucleon bombarding energy. The velocity distributions shift to slower velocities with increasing target mass showing that, on average, more mass is picked up from the heavier targets. The peak also broadens considerably when going from the ^{12}C to the ^{51}V target. Part of this width is due to the actual range of source velocities, arising presumably from different impact parameters, and part to the perturbation introduced by light-particle emission prior (preequilibrium and evaporation) and subsequent (evaporation) to heavy-fragment emission. The "evaporative component" of the width has been estimated with the statistical-decay code GEMINI,[11] filtered by the appropriate detector geometry, and is represented by the horizontal bars in Figs. 1(e)-1(h). In the case of ^{12}C, the width can be explained almost entirely by light-particle evaporation, showing that, due to the interplay between the incomplete-fusion mechanism and the complex fragment decay probability, a very limited range of source velocities contributes to complex fragment emission. However, this is no longer the case for the heavier targets, where a large range of source velocities and hence excitation energies is observed.

When the events are separated according to the fragment multiplicity [see Figs. 2(d)-2(f)], the requirement of a larger multiplicity of complex fragments selects out events with lower source velocities, i.e., higher excitation energies. For the ^{40}Ca target at $E_{\text{lab}} = 35$ MeV/nucleon, the incomplete-fusion picture gives upper limits to the peak "excitation energies" of 530, 660, and 750 MeV for twofold, threefold, and fourfold events, respectively. The same trend is observed for all targets. A similar result was recently observed in the Ne+Au reaction at 60 MeV/nucleon, but only for two- and three-body final states.[13]

To investigate the behavior of hot nuclear systems as their excitation energy increases, "excitation functions" for the multifold events have been constructed from the source velocity distributions. The cross section for multibody events at a given excitation energy depends on the probability of producing the decay nuclei for various reactions. In order to remove this dependence, we have determined the proportion of n-fold events with respect to the total number of coincidence events: $P(n) = N(n)/[N(2)+N(3)+N(4)+\cdots]$, where $N(n)$ is the number of n-fold events. Evaporation residues (one-body events) were not considered since in reverse kinematics they are confined to a very small angle around the beam direction where our detection efficiency is small. These probabilities have not been corrected for the detection efficiency. Such a correction requires knowledge of the precise kinematical nature of the events, such as mass distributions and relative velocities of the fragments, and will not be attempted here.

Rather than plotting these probabilities directly against the velocity of the source, we have chosen to plot them versus the quantity

$$Q = (E/A)_{\text{beam}}(V_s/V_b)(1 - V_s/V_b) .$$

This has the purpose of removing as much as possible the bombarding-energy dependence. In this definition Q would be an upper limit to the true excitation energy. Although this excitation energy may be in error by up to 30% due to the failure to account for preequilibrium particle emission in the incomplete-fusion model employed, such errors should only compress the energy scale and not destroy the simple pattern that is observed in the data.

The excitation functions exhibit several distinctive features (see Fig. 3). First, the probabilities for threefold, fourfold, and fivefold events increase substantially. Such behavior would be expected from any statistical model and supports a strong relationship between source velocity and excitation energy over the entire source velocity range studied. This dependence also confirms that the width of the velocity distribution is mostly due to the reaction dynamics, and is only partly due to evaporative

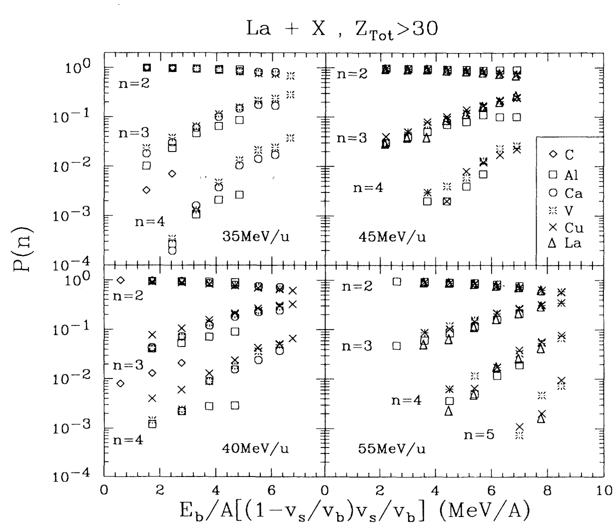

FIG. 3. Proportion of twofold, threefold, fourfold, and fivefold events as a function of excitation energy per nucleon (see text) for the targets (symbols, see inset) studied at $E_{\text{lab}} = 35$ (upper left), 40 (lower left), 45 (upper right), and 55 MeV/nucleon (lower right). The estimated masses of the hot nuclei vary from 145 at 2 MeV/nucleon to 175 at 6 MeV/nucleon.

broadening.

Second, the relative proportions of multifold events for all of the targets and the four bombarding energies *are very similar,* suggesting that the sources produced in these reactions depend mainly on how much mass is picked up by the projectile from the target and relatively little on the actual nature of the target.

A closer look at Fig. 3 shows a decrease of the multifold probability for the very light ^{12}C target. One possible contribution to these minor differences is the effective broadening of the excitation energy bins due to light-particle evaporation, which is particularly severe in the case of the very light ^{12}C target for which evaporation is a major contribution to the width of the source velocity distribution (see Fig. 1). In particular, this could also explain why at the highest excitation energies the multifold probabilities for the ^{27}Al target, which are in the tail of the source velocity distribution, fall slightly below those measured for the heavier targets. Moreover, the transition-state model of statistical decay[7] predicts a strong decrease of the complex fragment decay probability with decreasing angular momentum.[14] Thus, an additional source of the small differences for different targets could be that the hot nuclear systems are formed in the various reactions with slightly different angular momenta. However, we have no simple explanation of why the overall consistency seems to break down in the case of the very light ^{12}C target for which multifold events are less probable.

It is necessary to verify that the observed excitation functions are not strongly biased by some experimental artifact. Therefore, we have used the Monte Carlo simulations mentioned previously for the 35-MeV/nucleon ^{139}La+^{40}Ca reaction, assigning to events of all multiplicities the same source velocity distribution, thereby simulating flat excitation functions. After filtering by the detector acceptance, the calculated excitation functions for twofold and threefold events remain essentially flat. The simulated fourfold events decrease slightly at low excitation energies, whereas the experimental curve falloff is quite steep. We conclude that the detection efficiency is not skewing significantly the measured excitation functions.

Finally, the proportion of multifold events increases smoothly with Q or excitation energy up to approximately 6–8 MeV/nucleon. The statistical multifragmentation calculations of Bondorf *et al.*[3] predict a sudden rise in the multibody probability at $\sim$3 MeV/nucleon for a nucleus of mass 100. Gross, Zheng, and Massman[4] predict a similar transition towards nuclear cracking at an excitation energy of $\sim$5 MeV/nucleon for the ^{131}Xe nucleus. It would be necessary to filter such calculations by the acceptance of our detector system in order to make definite statements concerning their validity.

In this Letter we have demonstrated a technique which permits the characterization of hot nuclear systems and their decay over a wide range of source velocities and excitation energies using a single bombarding energy. The source velocity technique[8] was extended to multibody events and employed in conjunction with the incomplete-fusion model to estimate the excitation energy on an event-by-event basis. This, in turn, has allowed us to present excitation functions for multifragment events, which are observed to rise strongly with excitation energy. These excitation functions are largely independent of target-projectile combination and of bombarding energy, lending support to the idea of an intermediate nuclear system whose decay properties depend mainly on its excitation energy and angular momentum. In an attempt to reproduce these data on the formation and decay of hot nuclear systems, dynamical calculations followed by statistical-decay calculations are being undertaken, which will be filtered through the experimental detection efficiency.

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